A Proposed Role of Aeroelasticity in NASA's New Exploration Vision

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On 14 January 2004, NASA received a mandate to return astronauts to the Moon, evolve a sustained presence there, then head out into the solar system to Mars and perhaps beyond. This new space exploration initiative directs NASA to develop human and robotic technologies that can deliver payloads larger than Apollo to the Moon, to Mars, and bring astronauts and samples safely back to Earth at costs much lower than Apollo. These challenges require creative aerospace systems. One proposed technology for safely delivering payloads to the surface of Mars and returning samples to Earth involves deployed flexible and inflatable decelerators for atmospheric entry. Because inflatable decelerators provide the entry vehicle more drag surface area at smaller mass than traditional ablative devices, this class of decelerators can potentially accomodate larger mass payloads. The flexibility of these lightweight aeroshells can pose both vehicle and aeroelastic stability problems if not properly designed for the expected flight regimes. Computational tools need to be developed for modeling the large and nonlinear deformations of these highly flexible structures. Unlike wind tunnel testing, an integrated and efficient aeroelastic analysis tool can explore the entire flight environment. This paper will provide some background on flexible deployable decelerators, survey the current state of technology and outline the proposed development of an aeroelastic analysis capability.

Key words: Aeroelasticity, Unsteady Aerodynamics, Flutter, Ballute.

Introduction

NASA'S new space exploration initiative has set a new course to develop human and robotic technologies that can deliver payloads larger than Apollo to the Moon, to Mars, and bring astronauts and samples safely back to Earth at costs much lower than Apollo. These challenges require creative aerospace systems. One proposed technology for safely delivering payloads to the surface of Mars and return samples to Earth involves flexible, deployable, perhaps inflatable decelerators.

Because deployable decelerators provide the entry vehicle more drag surface area than can be packaged inside a launch shroud in a single piece, this class of decelerators offers the potential of delivering larger size and higher mass payloads to the surface of Mars or Earth.[1,2] The flexibility of lightweight, inflatable aeroshells poses stability problems if not properly designed for the expected flight regimes.

The flight regimes for a Mars landing or Earth reentry encompass the hypersonic to subsonic with varying temperatures and dynamic pressures. Computational tools for modeling these flow regimes on stiff structures such as wings and tails must be adapted to handle flexible structures whose deformations are likely to be large and nonlinear. Several technical challenges are expected: 1) the fluid/structure coupling of a highly flexible structure to a computational fluid dynamics code ; 2) the nonlinearity of both the fluid and structures codes; 3) analytical and finite element modeling of complex nonlinear membrane behavior; and 4) experimental validation of the structural modeling and the aeroelastic analysis method.

An integrated, coupled analysis tool could explore the entire trade space more economically and effectively for aeroassist at Mars, Venus, Titan, Neptune, Earth (sample return scenario) and other bodies in our solar system. It would strongly enhance industry capability while advancing the state-of-the-art in inflatable aeroassist devices. It may also ameliorate the need for the expensive experimental testing on which static and dynamic vehicle and aeroelastic stability data are currently based. Benchmarked capabilities would provide clearly defined expectations and figures of merits for comparing analysis tools. This paper will provide a brief history of flexible deployable decelerators, survey

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Fig. 1 Trailing ballute.

Fig. 2 Attached or clamped ballute.

existing experimental methods and analyses and outline a proposed aeroelastic analysis capability and its experimental validation.

Deployable Decelerator Background

Several classes of deployable decelerators have been considered, built, and tested. They fall within two categories. The first is a trailing ballute in the form of a toroid connected to the payload by tension lines, shown in figure 1. The second is an attached ballute where fabric fills the space between the nose and the trailing edge, figure 2. Several concepts for ballutes are presented.

Attached Inflatable Decelerator

One reentry concept is the Attached Inflatable Decelerator (AID). This concept involves a ballute attached directly to a blunt conical body. A standard ballute is a trailing balloon-parachute, first conceived as a towed supersonic decelerator. Attachment of the ballute to the aeroshell in an AID device avoids the instability problems of a trailing decelerator. The Goodyear Aerospace Co developed an early AID,[3] tucked in the rear of the vehicle body. Advantages of that design were significantly decreased volume and inflation time.

Early AID testing of small-scale wind tunnel models was performed at speeds from subsonic to greater than Mach 3. In a test of in situ inflation performance, a packed AID was released and rapidly inflated at the reentry velocity. Rapid inflation was required to preclude waves running from the blunt conical body to the rear of the ballute that increased in frequency as the ballute inflated.[45]

Most previous AID testing of subscale flutter models found no flutter in the relatively small fully inflated models.[6] After a sustained period of wind tunnel time at angle of attack, one ballute model showed signs of tearing.[7] Other static inflation tests were performed to determine the internal pressure at failure.[8] The addition of meridian tapes and localized reinforcement increases overall strength, but also altered load paths and failure modes. With the addition of meridian tapes, failures typically occurred at the wrinkles near a load cell.

To enhance vehicle stability at low Reynolds numbers, a ballute may require a transition tripping device. In one instance a small lip was installed around the maximum diameter in order to induce a uniform transition. The original Goodyear designs had an inflatable burble fence. Another study found that a fluttering ribbon produces a similar result.[7]

More advanced AID concepts are being designed. One recent concept is the Russian IRDT,the Inflatable Re-entry and Descent Technology,[9] developed for use on the International Space Station.The IRDT concept uses two-stage inflation. In the first step, a smaller AID ballute is inflated for reentry. In the second, a tension shell is inflated after reentry to further decelerate the payload.

Tension Shell

Tension shells are another early reentry concept designed to maintain tension forces in the center of the reentry body with compressive forces at the nose and the tail.[10] This allows the area of the reentry body in tension to be composed of a membrane, thus reducing weight over conventional ablation shields. See figure 3. Testing has assessed potential failure modes for various configurations. In one test, failure of the compression ring in the tension shell was observed to

Fig. 3 A tension shell concept.

create ripples and buckling in the mid-body.[11]

Rotornet

The final of the early attached deceleration devices is the rotornet. The rotornet consists of an isotensoid disk, created from a net that is wound around a payload and spun at high speeds.[12] Extensive research was performed to determine instability modes. The first is column instability, which is essentially rigid body circular panning. This instability can be countered with higher coning angles or with a greater attachment radius. The second instability is spiral instability. This was found at low coning angles, and can be reduced by a greater coning angle or an active control system. The third instability was disk flutter. This can be addressed by using active control, or by a passive spring/damper system. Another method of stabilization is the use of vanes or tabs along the outer perimeter of the rotornet.[12]

Current Aeroelastic Analysis Methods

Linear methods are well understood and applied to the aeroelastic analyses of relatively stiff lifting surfaces. Already these methods have been applied to the designs of the space shuttle, and to other space vehicles intended to encounter the atmosphere of a planet, such as the Mars Airplane concept called ARES (Aerial Regional-scale Environmental Survey).[13–15] These same linear methods are ready for analyzing competing designs of the Crew Exploration Vehicle (CEV) that is planned for taking the astronauts to the Moon or to Mars and safely returning them to Earth.

Nonlinear methods are currently under development for meeting an objective of improved fidelity in current aeroelastic analyses for subsonic, supersonic, and hypersonic flight regimes. However, these methods are being applied to relatively stiff aerospace structures that behave linearly, or proportionally, to the applied aeroloads which are being represented by time invariant nonlinear and linear terms.

These methods do not require the coupling envisioned for analyzing the designs of flexible, deployable, possibly inflatable entry devices, such as that shown in figure 1. The limitations of existing modeling tools will require their enhancement or possibly the development of new techniques.

Recent Studies Under the ISP Program

Through NASA's In-Space Propulsion (ISP) program, a preliminary examination of sensitivity to geometry and Reynolds number and the influence of large displacements on aeroheating and dynamic pressures was conducted.

Analysis

The operating regime of the ballute will be low density and Reynolds number and high total specific enthalpy.[16] Previous Computational Fluid Dynamic (CFD) studies have investigated the interaction of the spacecraft wake and aeroheating and its sensitivity to geometric and Reynolds number variations.[17] Of the various configurations studied, towed, clamped ballute and toroidal, the clamped and toroidal ballute systems appear to offer the most advantage with regard to aerothermal effects. One of the significant findings of these studies is that the wake can be unsteady in some configurations, notably when the vehicle shock impinges on the towed ballute bow shock.[18] This has motivated the investigation of a toroid-shaped ballute. In a tethered toroidal ballute the vehicle bow shock is swallowed within the toroid and the vehicle/ballute bow shock interaction is well behind the torus. In this configuration static aerothermoelastic interaction will be the primary concern as long as shock to shock interaction remains benign. In another configuration the torus is connected to the vehicle by a conically shaped thin-film chute. A single bow shock envelopes the entire vehicle and ballute. Both static and dynamic aerothermoelastic interactions can occur. In any configuration high heating rates will also be important as they influence the behavior of the structure.

A computational investigation of the effect of large displacements on aeroheating and dynamic pressures has also been conducted. Pressures and temperatures were computed using CFD for a rigid aeroshell design and passed to a nonlinear geometric finite element program to solve for the final deformed shape. The CFD grid locations were subsequently updated based on the final deformed shape and new pressures and temperatures were computed. The deformed shape allows for a circulation pattern within the flexible trough between the nose and the trailing edge, resulting in local increases and decreases in temperature and pressure along the aeroshell outer wall. Several key accomplishments were realized. First, the analysis provides a quantitative assessment of heating associated with

aero deformations of clamped ballutes through single-pass coupling between an aero code and a finite element solver. Second, the results provide the first and only confirmation that axisymmetric, 1st-order time accurate solutions can reproduce to a qualitative extent the unsteady motion and discern bounds between trailing toroidal configurations that support steady and unsteady flow. Third, the results provide a quantitative assessment of tether heating. Finally, these results underscore the need to analyze the modal response of the structure to unsteady pressures and temperature.

Wind Tunnel Testing

A suite of high speed wind-tunnel tests was established in the ISP program with the following objectives: 1) develop methodology and precedence for testing flexible materials in hypersonic facilities; 2) evaluate advanced materials in a high-temperature, high-speed flow environment; and 3) provide experimental data for comparisons with aerothermoelastic modeling software tools. Several wind-tunnel models were built out of plastic support structure and polyimide membranes to represent an attached ballute concept. Several membrane thicknesses and cone angles were tested up to Mach 10 and Reynolds number just over 525,000/foot. Some of the models could not withstand the combination of dynamic pressures and temperatures, resulting in failure of the polyimide membrane. These results underscore the need to better understand the combined loads for designing the ballute structural components.

Proposed Wind Tunnel Testing for Tool Validation

A new test program of a larger scale aeroelastic model is planned for the NASA Langley Transonic Dynamics Tunnel (TDT). The role of testing will be to assess the size scalability of manufacturing techniques and material quality and to provide data for calibration of analytical models and validation of computational tools. These roles conflict in that acquiring quality data for computational tool validation necessitates a model that is small relative to the tunnel size. On the other hand, testing size scalability is best served with a full scale model. Because of the impracticality of testing full scale models, gossamer structural testing has made extensive use of component testing and fabrication.[19] Large scale component testing of this nature will be performed under the present project. Yet the successive testing of larger-scale, fully assembled ballute models in different scale tunnels builds confidence in the processes developed for manufacturing and assembly. The TDT test will be the largest assembled ballute model wind tunnel test envisioned under the program.

Challenges of Tool Validation by Experiment

The most difficult role of the TDT test will be to provide data for validation of computational and analytical tools. There are several challenges in obtaining experimental data of a highly flexible and nonlinear structure for tool validation. These fall under the headings of structural characterization, model sizing and data sensing technology.

First, experimental characterization of a flexible, nonlinear film structure is difficult.[20–23] Kapton polyimide films are known to be materially and geometrically nonlinear with frequencies and damping variations due to loading and excitation level. Studies of gossamer structures of a size comparable to that expected in the proposed test show that a significant component of the total deflection is due to gravity force.[21] In an effort to reduce the component due to gravity, test articles have been oriented for static and modal testing to minimize the gravitational effect.[19] Yet it may still be necessary to model the gravity force in the computations.[19,21] Because of the high flexibility and low mass per area, air forces will likely preclude a realistic in vacu modal characterization of the structure unless tested in a vacuum. A vacuum chamber test is planned for the current project.

Highly flexible structures are also very sensitive to boundary constraint orientation and distribution and manner of load application. To illustrate the difficulties of testing, in one test extensive refining of test techniques on simple Kapton thin film strips was required to make it possible to discriminate many of the issues related to boundary treatment.[23] The designers of gossamer solar sail models have identified edge constraints as having considerable influence on static and dynamic behavior.[20] Furthermore, wrinkling due to edge constraints diminishes model usefulness and excessive wrinkling and creasing over significant portions of the model will alter membrane stiffness, damping, mode shapes and frequencies of even the lowest modes.

Attention must also be paid to the manner in which the film structure is dynamically excited. Many researchers have used force excitation applied directly to the membrane. This produces uneven membrane motion due to the considerable membrane compliance. A more effective approach may be to use an electromagnetic voice coil shaker,[23] producing a more evenly distributed film excitation.

The second challenge is the constraint on the size of the model in relation to the wind tunnel. Model blockage and wall interference always influence the flow field near a vehicle in wind tunnel tests. This in turn influences the data taken. The influence of model blockage and wall interference is made more prominent as the model size increases. Most prior wind tunnel testing has been performed for aerodynamically smooth vehi-

cles. An additional constraint by the purpose of the ballute which is to effectively impede the flow around the vehicle, thus disrupting the surrounding flow. This increases the relative extent to which tunnel blockage and wall interference alters the validation data acquired. Therefore, careful attention to the model definition and sizing will be required to ensure that excessive tunnel wall interference is not induced if data is to be acquired for validation of free air computational models.

The third difficulty in experimental testing is the acquisition of measurements on the membrane surface. The sensors used in stiff aeroelastic models are inappropriate except for measurement of loading, accelerations and pressures at rigid model points. Current data acquisition across a membrane surface has been limited to measurements of deflections. Several methods of varying degrees of accuracy have been used. Photogrammetry with digital cameras and videogrammetric model deformation (VMD) measurements have been acquired using targets on the membrane surface.[20] Targets alter both the mass and the local stiffness of a thin film membrane. The use of a moderate number appears to affect only local details such as wrinkling;[19] however, it may be necessary, in the computational validation stage, to model the target dynamics. Other examples of devices used are the Leica Laser Radar system for static deformation measurement,[20] and the Polytec PI PSV-300 scanning laser vibrometer.[23]

Proposed Computational Approach

In order to assess as efficiently as possible the influence of flow/structure interaction on the ballute design, several levels of analysis fidelity will be used. Static aerothermelastic analysis will assess the influence of statically deflected shape on ballute performance and heating rates. The onset of flow-induced unsteadiness can also be predicted using a static flow/structure interaction, as illustrated in a previous section of this paper. Dynamic aerothermoelastic analysis will primarily address membrane flutter onset. In addition to the danger of component failure, aeroelastic response of the inflated toroid can also result in undesirable vehicle response. The interplay between component aeroelasticity and overall vehicle stability may require an integrated fluid/structure and vehicle analysis as well.

Mathematically the flow field and structure for both the static and dynamic aeroelastic analysis will be treated as separate domains coupled by an interface. Static aeroelastic analysis can be performed in a loosely coupled manner. The coupling of the fluid and structure can be catagorized under the headings of loose and close coupling. A closely coupled approach can be defined as that in which the structure is treated within the CFD code either modally or by direct solution using a mesh that is coincident with the flow field mesh. We define the loosely coupled approach to be one in which the CFD and CSD (Computational Structural Dynamics) or FEA (Finite Element Analysis) codes are separate but coupled via a fluid/structure coupling mechanism.

When the flow field and structure are solved as disparate domains, a coupling mechanism is required allowing a reciprocal exchange of data between codes. The hypersonic flow/structure interaction requires transfer of pressures as well as heat flux and temperature. The fluid/structure coupling can be accomplished using several available packages. NASA Langley has developed a multidisciplinary code interface using Non-Uniform Rational B-Splines (NURBS).[24] Several commercially available packages allow coupling of CFD and FEA codes, such as MpCCI (Mesh-based parallel Code Coupling Interface)[25] and MDICE (Multi-Disciplinary Computing Environment).[26] As a recent example, unsteady hypersonic aerothermoelastic analysis has been performed for the design of thermal protection components in a reentry vehicle using the MpCCI coupling.[27]

Membrane details have been shown in previous studies to profoundly influence overall structural performance. Seams have much higher moduli than the film otherwise has and significantly alter ballute stiffness properties. Pressurized polyimide film structures are highly nonlinear, with responses that vary with excitation level and moduli (and thus frequencies) that depend strongly on pressurization.[28] Film wrinkling also alters the structural response. The analysis technique must be capable of addressing these structural details. Several FEA codes under consideration within the NASA Langley Research Center effort are MSC NASTRAN, MSC Marc and ABAQUS.

A requirement of the FEA will be the capability to model a membrane thermoelastically, including structural nonlinearities due to thermal effects, thermal strain and creep, as well as the influence of thermal radiation. However, not all FEA tools have adequate modeling capabilities. Considerable effort in recent years has been applied to development of membrane modeling capabilities. Recent work has advanced the capability to model membrane wrinkling, creases due to folds, and a variety of edge constraints, as well as nonlinear thermal effects.[19,22,28–35] Methods of analysis and models that incorporate these effects are being developed within both NASTRAN and ABAQUS, as well as other research codes.[36] The present effort will leverage the available recent development.

The operating environment will span the rarified to continuum flow regimes, however, the highest loading

is expected to be within the continuum flow regime. The primary aerothermodynamic codes to be used within the NASA Langley Research Center effort for aerothermoelastic analyses are LaURA,[37] FUN3D,[38] and CFL3D.[39] These codes have, or will have incorporated, the appropriate aerothermodynamic models including equilibrium, non-equilibrium chemistry and surface catalycity. Since the coupling of several computationally intensive analyses such as Navier-Stokes CFD and an FEA code will be prohibitively expensive for routine flutter analyses, several levels of code fidelity will be required. Recent preliminary analyses of configuration sensitivities have ignored real gas, rarified gas and viscous effects.[18] In the present study, initial aerothermoelastic computations can be performed at this level. However, because of the complex vehicle ballute shape and high Mach number, laminar and possibly transitional viscous analysis of selected conditions will be required. Where turbulent computations are required, recent studies suggest that the shear stress transport (SST) model of Menter provides reasonably accurate results for turbulent hypersonic flows.[40] Static aeroelastic analysis can be performed with these successive levels of fidelity using a loose coupling of the CFD and FEA codes.

Prediction of the onset of flutter will require additional closely coupled analyses. Hypersonic panel flutter and hypersonic vehicle aeroservoelastic stability have been addressed through well established hypersonic aeroelastic analyses. The aerodynamic theory for these analyses have typically been classical or generalized linear and nonlinear piston theory, hypersonic small disturbance theory or the perturbed Euler method.[41,42] These require the assumption of a thin body and sharp leading edge and can be reasonably applied to lifting surfaces or sharp nosed bodies of revolution. Aeroelastic analysis of bluff bodies has received much less attention owing to the complexity of the flow field behind a detached bow shock and the necessity of including viscous effects. For flutter onset analysis of the thin-film ballute, a time marching closely coupled solution of the hypersonic flow field and modal equations of the film structure will be used. When possible, system identification or order reduction techniques will be used to spare computational effort. In a recent example of such an analysis, Euler and Navier-Stokes aerothermoelastic computations have been performed for flutter onset of isolated wings and a generic reentry vehicle at Mach 10-15.[39,43–45] The wing structure was modeled in a modal sense within the CFD code and various system identification techniques used to determine flutter onset. An interesting outcome of one of those studies is the importance of viscous effects even in computing flutter onset for a relatively thin wing in hypersonic flow.[39]

Concluding Remarks

As the survey presented in this paper indicates, the aeroelastic analysis of a thin-film ballute will be a major technical challenge. Many issues will have to be addressed at the structural and aeroelastic testing and the computational modeling stages. Verification of the finite element structural model and the coupling procedures will be required before these tools can be used for design. Material properties such as the moduli of adhesive bonded seams or thermal behavior will be validated with material test data, and the overall ballute finite element model validated with ground test data. Established procedures of analysis will be followed such as those outlined in this paper, for membrane modeling, modal analysis and for the coupled fluid/structure integration and aeroelastic analysis. Validation will be conducted by comparisons of both static and dynamic aeroelastic response with wind tunnel test measurements. These steps should give the confidence necessary for use in the full scale design.

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